



Shielding Effectiveness Measurements Applied to Safety Assessment Predictions at Picatinny Arsenal

by Neal Tesny, Marc Litz, David Conrad, and Lillian Dilks

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14. ABSTRACT Shielding effectiveness for a screened work area in building 3208 of the Picatinny Arsenal has been measured using techniques and processes defined in MIL-STD 188-125-1. The measured frequency ranges go beyond the MIL-STD 10 MHz to 1 GHz, to include the frequency range of 1 to 10 GHz. The results of the measurements show that attenuation factors provided in the current configuration are sufficient to provide acceptable environmental and safety protection from high-power RF impulse sources radiated from within.					
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1. Introduction

Shielding effectiveness measurements for the 20 MHz to 10 GHz frequency band were made for the shielded room that is partially lined with microwave absorber, located in building 3208 of the Picatinny Arsenal. The measurements were performed 18 to 20 January 2005. The shielded area is constructed from plywood surrounded by a layer of sheet metal on either side of the plywood. The room has a double-door and several patch panels. The shielding effectiveness of this type of room, as originally installed by the manufacturer, is typically on the order of 60 dB over the 20 MHz to 1 GHz frequency band.

Over years of use, the room has been modified for many experiments critical to understanding the susceptibility of army materiel. Regular use and modifications will leave a shielded room with shielding parameters below those originally specified by the manufacturer. While the shielding may be below original manufacturer specification, it is our goal to verify that the shielding status is sufficient to provide a safe working environment for personnel operating in the building. The measurements described below give a status report of the level of shielding provided by the current physical configuration. While attempts will undoubtedly be made in the future to improve the shielding effectiveness, we will not make those suggestions in this report, as that is not the goal of this effort.

The measurement techniques followed in this report adhere to standards developed within the Department of Defense to evaluate the shielding effectiveness of shielded rooms. A quantitative question that arises during this effort pertains to the field strengths that would be necessary to go beyond environmental safety limits. The safety office at Army Research Laboratory (ARL) follows a policy of as-low-as-reasonably-acceptable. Typical safety levels for peak radio frequency (RF) impulses are limited to 1 kV/m at the edge of the facility fenceline. Prediction of the fields required to produce these limits would help develop guidelines for future operations of high-power RF sources within the shielded room and facility.

2. Measurement Methodology

The measurement methodology is based on guidance described in MIL-STD 188-125-1, "High-altitude Electromagnetic pulse (HEMP) Protection for Ground-based C4I Facilities Performing Critical, Time-urgent Missions, Part 1 Fixed Facilities," 17 July 1998. Although this standard was written for a shielding effectiveness threshold of 80 dB over the band measured, the methodology is applicable for the measurement focused on safety and environmental hazards associated with usage of the bldg 3208 RF shielding levels.

The MIL-STD calls for the spacing of test frequencies to be logarithmic within each decade with a minimum sampling density as follows:

10 kHz	–	100 kHz:	20 test frequencies
100 kHz	–	1 MHz:	20 test frequencies
1 MHz	–	10 MHz:	40 test frequencies
10 MHz	–	100 MHz:	150 test frequencies
100 MHz	–	1 GHz:	150 test frequencies

The goal of these measurements was focused on safety assessment. Therefore, the envelope of frequencies of interest included higher frequencies from those developed for HEMP hardening goals. Our final frequency range of interest covered from 300 KHz to 10 GHz. Traveling wave tube (TWT) amplifiers were used in performing the attenuation measurements over the frequency range from 1 to 10 GHz.

3. Description of Measurements

Initial plans called for shielding effectiveness measurements on the enclosure to be made at a total of nine test points, eight of them located on the side walls and one point on the ceiling. The points are identified in figure 1. However no data was measured for test points four and five because no unobstructed position within five feet of the shielded room wall was available for access to these points. The frequency bands that were tested ranged from 300 KHz to 10 GHz and are shown in table 1 with the corresponding test points. An HP 8753 network analyzer was used for all measurements below 3 GHz. The network analyzer was programmed to sample data at 401 test frequencies in each of the test bands, i.e., between 300 KHz and 20 MHz, 20 MHz and 1 GHz, 1 GHz and 2 GHz, and between 2 GHz and 3 GHz. In the 300 KHz-20 MHz and 20 MHz-1 GHz bands the frequencies were distributed logarithmically, i.e., \log_{10} of the frequencies was uniformly spaced between $\log_{10}(20 \text{ MHz})$ and $\log_{10}(1 \text{ GHz})$. In the 1 to 2 GHz and 2 to 3 GHz bands the frequencies were linearly distributed. Resolution bandwidth was set at 10 Hz resulting in a sweep time of about 42 seconds. For the measurements in the frequency range of 300 KHz to 20 MHz, an AH Systems SAS 562 a powered loop antenna was used to receive signals, and a passive tri-loop antenna of approximately 20-inch diameter powered by an ENI 2100 power amplifier was used to transmit. For the measurements in the frequency ranges of 20 MHz to 1 GHz, 1 GHz to 2 GHz, and 2 GHz to 3 GHz two Bi-logic log-periodic antennas were used. The amplifiers used were an Amplifier Research 10W1000 for the 20 MHz to 1 GHz range, a Varian VZL-6941K1 TWT for the 1 to 2 GHz range, and a Varian VZS6951K1AD TWT for the 2 to 3 GHz range. The data was downloaded from the network analyzer to a laptop computer. Both horizontal and vertical polarizations, with respect to E-field, were measured at each test point and frequency band, with the exception of the 3 to 4 GHz range which used the conical spiral antennas which have circular polarization.

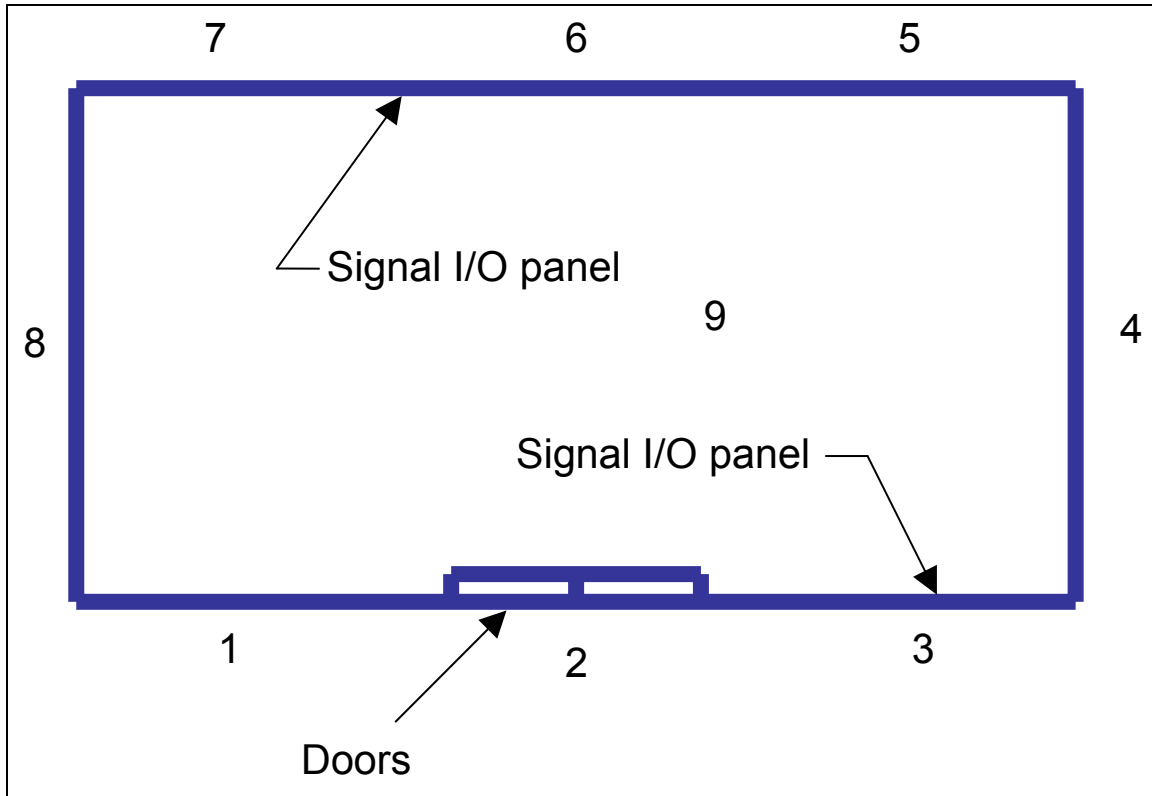


Figure 1. Top view of enclosure showing test point locations.

Table 1. Matrix of measurement sets acquired for shielding effectiveness evaluation.

Measurement Hardward Matrix					1	2	3	4	5	6	7	8	9
Frequency range	Signal connection	Antenna	Analyzer	Sampling									
.3-20 MHz	Fiber	Loop	NA	401 pt log	√	√	√			√	√	√	√
.02-1 GHz	Fiber	Bilog	NA	401 pt log	√	√	√			√	√	√	√
.02-1 GHz	Direct link	Bilog	NA	401 pt log	√	√	√						
1-2 GHz	Direct link	Bilog	NA	401 pt lin	√	√	√			√	√	√	√
2-3 GHz	Direct link	Bilog	NA	401 pt lin	√	√	√			√	√	√	√
3-4 GHz	Direct link	Bilog	SA	11 pts lin	√	√	√			√			
4-6 GHz	Direct link	OEW (4-6 GHz)	SA	11 pts lin	√	√	√			√			
6-8 GHz	Direct link	OEW (4-6 GHz)	SA	11 pts lin	√	√	√			√			
8-10 GHz	Direct link	OEW	SA	11 pts lin	√	√	√			√			

For the frequency ranges above 3 GHz an HP 8563A, a spectrum analyzer was used to collect relative signal levels at discrete frequency points spaced linearly every 100 MHz, with an HP8350B sweep oscillator used to generate the signals. For the frequency range from 3 to 4 GHz, a Varian VZS6951K1AD TWT amplifier was used along with a pair of Emco 3102 conical spiral antennas. For the frequency range from 4 to 6 GHz, a Hughes 1177H C-band TWT amplifier was used along with a pair of WR-187 open-ended waveguides as transmit and receive antennas. For the frequency range from 6 to 8 GHz, a TWT amplifier was used along with a pair of WR-137 open-ended waveguides. For the frequency range from 8 to 10 GHz, a

Hughes 1177H X-band TWT amplifier was used along with a pair of WR-90 open-ended waveguides.

Measurements above 3 GHz were performed only for test points 1, 2, 3, and 6. No measurements were performed for test points 7, 8, and 9 between 3 to 10 GHz. Time constraints of the test team limited the total number of measurement options. If the information is deemed necessary, future testing will be arranged.

The MIL-STD states that separation between transmit and receive antennas shall be 10 feet (± 2 inches). This distance was used for measurements in the frequency bands less than 3 GHz. However, above 3 GHz we found that a separation distance of 5 feet could be used to obtain a better signal-to-noise ratio while remaining in or near the “far field” and therefore, this separation distance was practical for this series of measurements.

Calibration measurements for both horizontal and vertical polarizations (with reference to the log periodic portion of the antennas) were obtained at an antenna separation of 10 feet for the test frequency bands 300 KHz to 20 MHz, 20 MHz to 1 GHz, 1 GHz to 2 GHz, and 2 GHz to 3 GHz, and at horizontal and vertical polarizations at an antenna separation of 5 feet for the frequency bands 3 to 4 GHz, 4 to 6 GHz, 6 to 8 GHz, and 8 to 10 GHz. The conical spiral antennas used in the 3 to 4 GHz band are circularly polarized; therefore, a single calibration was performed. The measurements were performed in the open area outside of the shielded room in the building. For the frequency bands 300 KHz to 20 MHz and 20 MHz to 1 GHz, a fiber optic cable system was used to transmit frequency information from the network analyzer to the amplifier. RG-223 double-shielded RF cables were used to connect the network analyzer to the fiber optic transmitter, the fiber optic receiver to the amplifier, the amplifier to the transmit antenna, and the receive antenna to the network analyzer. The output signal of the receive antenna was attenuated by a single high-power 40 dB attenuator, prior to being fed to the network analyzer. This technique prevented overloading the input to the network analyzer. The 40 dB attenuator was calibrated separately at the 401 test frequencies corresponding to each of the two bands using the network analyzer in order to account for its presence in the receive circuit.

For the frequency bands above 1 GHz, a direct feed was used in place of the fiber optic link. This direct link used the type N bulkhead feed-through in the I/O panel in the front of the enclosed room.

For the frequency bands up to 3 GHz, the network analyzer, receive antenna, fiber optic transmitter (which was used up to 1 GHz) and laptop computer were placed inside the shielded room for the shielding effectiveness measurements. One end of a fiber optic cable was connected to the transmitter. The fiber optic cable passed through a hole in the shielded room I/O panel to exit the shielded room so that the other end could be connected to the fiber optic receiver. The amplifiers and transmit antenna were also outside the shielded room. For the frequency bands above 3 GHz, the spectrum analyzer and receive antennas were placed inside

the shielded room, and the amplifiers and transmit antennas were placed outside the shielded room.

A diagram of the shielding effectiveness measurement system is shown in figure 2. This shows the configuration which uses the fiber optic link. The output of the network analyzer (O) is split so that a reference signal (R) can be provided to compare with the signal received by the receive antenna (A). For a given frequency and polarization, the difference in intensity between the received signal and the reference signal is called A/R. A/R is a measure of the signal loss at that frequency due to the path between the transmit antenna and the receive antenna plus additional losses and gains due to the various components in the transmitting and receiving circuits including cables, the signal splitter, fiber optic equipment, amplifier and antennas. The shielding effectiveness at a given frequency is the difference between this value and the value at that frequency obtained when the system was calibrated, i.e., when there were no shielded room walls between the transmit antenna and receive antenna. This technique is based on the fact that the additional system and component losses and gains described above are assumed to be the same for the calibration measurement and the shielding effectiveness measurement.

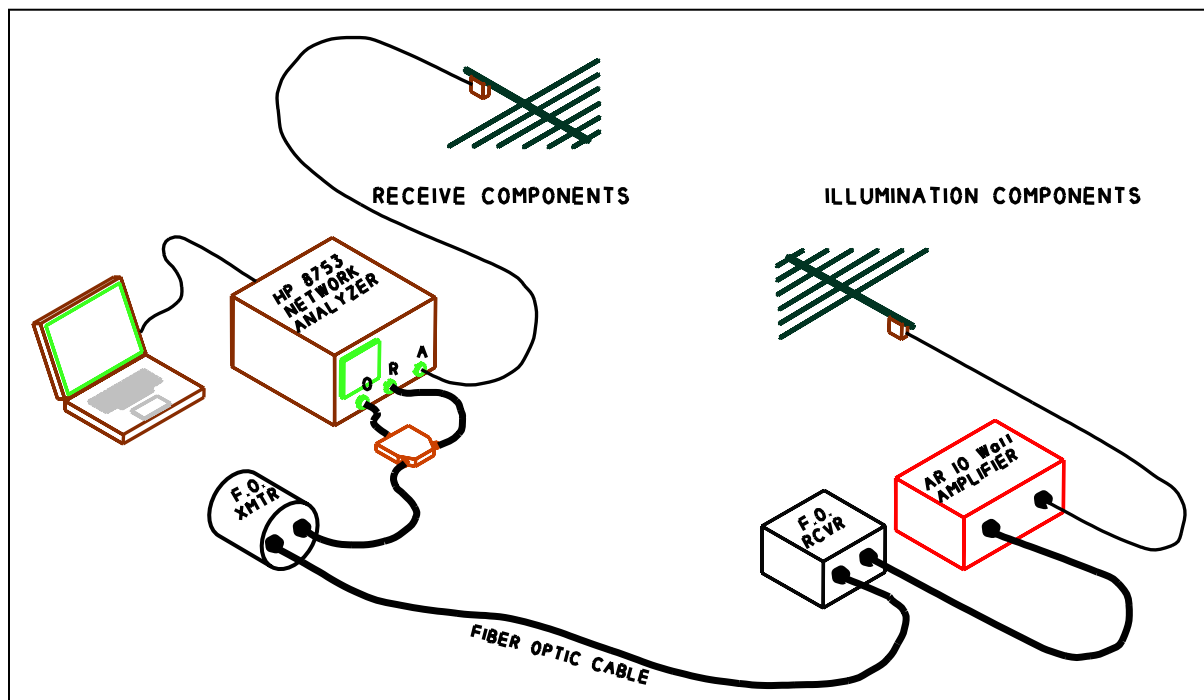


Figure 2. Electrical schematic for equipment and instrument control. This hardware schematically describes the test equipment used during these safety measurements.

Four measurements were recorded at each test point using the 8753 network analyzer. These were 1&2) a noise floor measurement in both vertical and horizontal polarizations and 3&4) a shielding measurement in each polarization. Each noise floor measurement was taken with no signal being transmitted, thus providing the background noise level needed to determine the dynamic range for each point and antenna orientation. The shielding measurements were taken

with the amplifier on and sending the appropriate signals to the transmit antenna. These signals were provided by the network analyzer via the fiber optic cable link.

For the measurements above 3 GHz, a sweep oscillator connected to a TWT amplifier was used to produce signals spaced every 100 MHz in frequency which were transmitted on the exterior of the shielded room. The signal levels were then read from an HP8563A spectrum analyzer located inside the shielded room. For the frequency range from 3 to 4 GHz, a pair of Emco 3102 conical spiral antennas was used as transmit and receive antennas. For frequencies above 4 GHz, matching open ended waveguides, within the bands described in table 2, were used as transmit and receive antennas. In order to obtain the noise floor, the signal level was obtained from the spectrum analyzer when no signal was being transmitted.

Table 2. Resonant frequencies of a $28' \times 12' \times 8'$ box based on full-wave and half-wave resonances.

Length (ft)	(m)	Freq (MHz)
28	8.48	35.4
12	3.64	82.5
8	2.42	123.8
56	17	17.7
24	7.27	41.3
16	4.85	61.9

4. Results

Data for each test point and polarization was combined in a large array containing results of all measurements. Plots of these arrays for each of the test points for horizontal and vertical polarization are shown in figures 3 through 9. The data are plotted along with the dynamic range of the measurement system for comparison. Measurements were not made for test points four and five because no unobstructed position within five feet of the shielded room wall was available for access to these points. The matrix of measurement sets is shown in table 1.

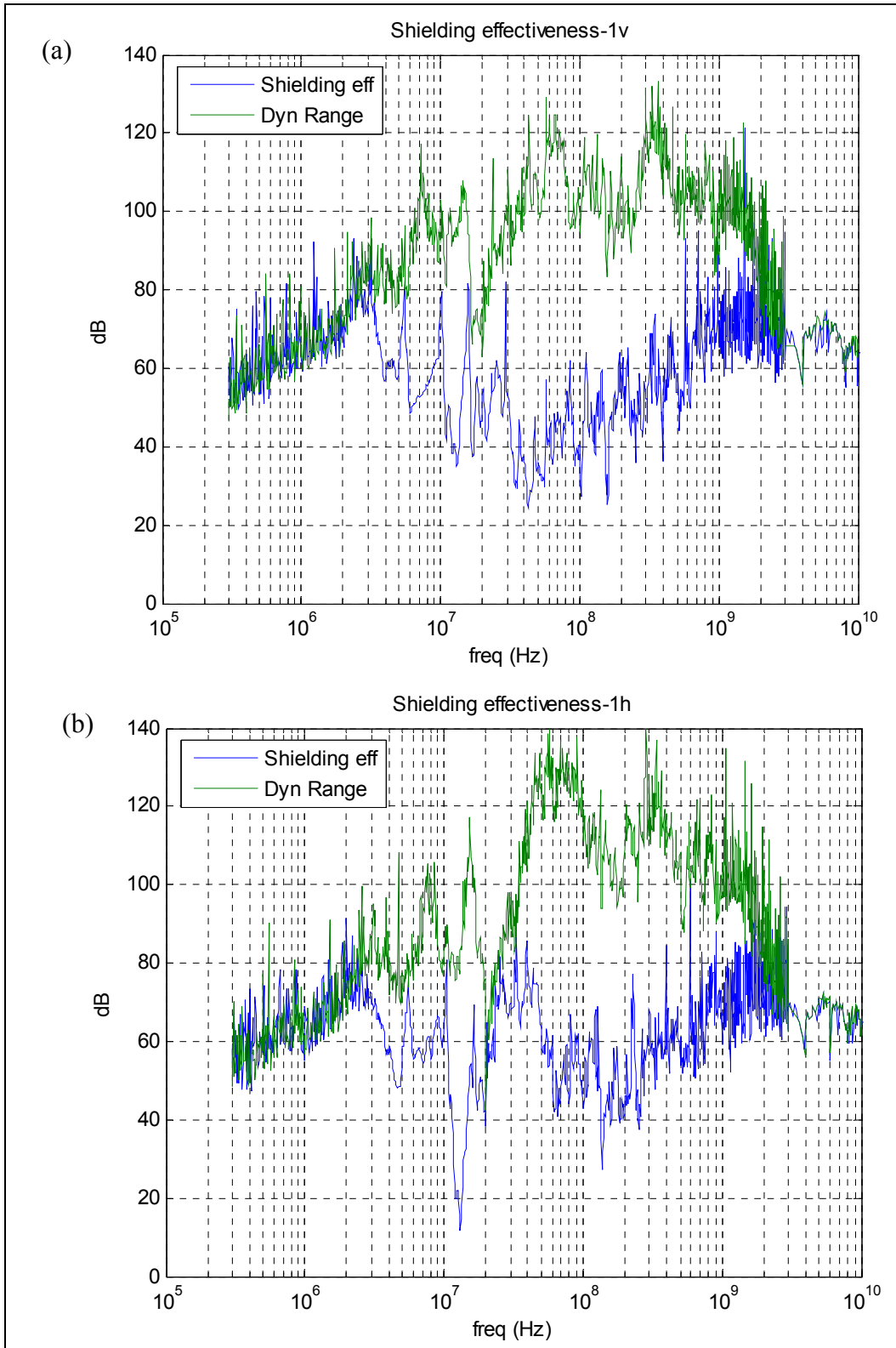


Figure 3. Shielding effectiveness for test point 1, (a) vertical polarization and (b) horizontal polarization.

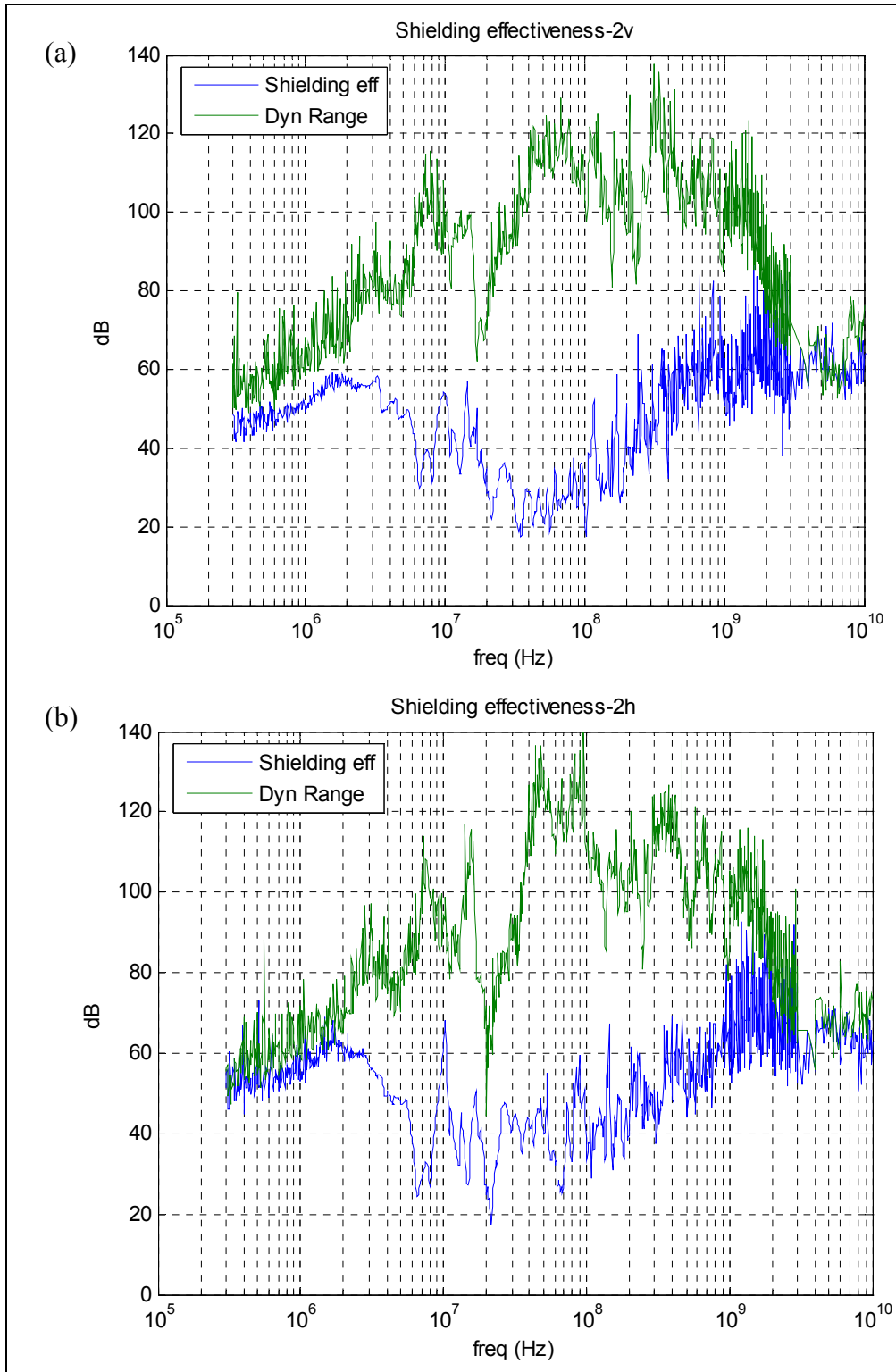


Figure 4. Shielding effectiveness for test point 2, (a) vertical polarization and (b) horizontal polarization.

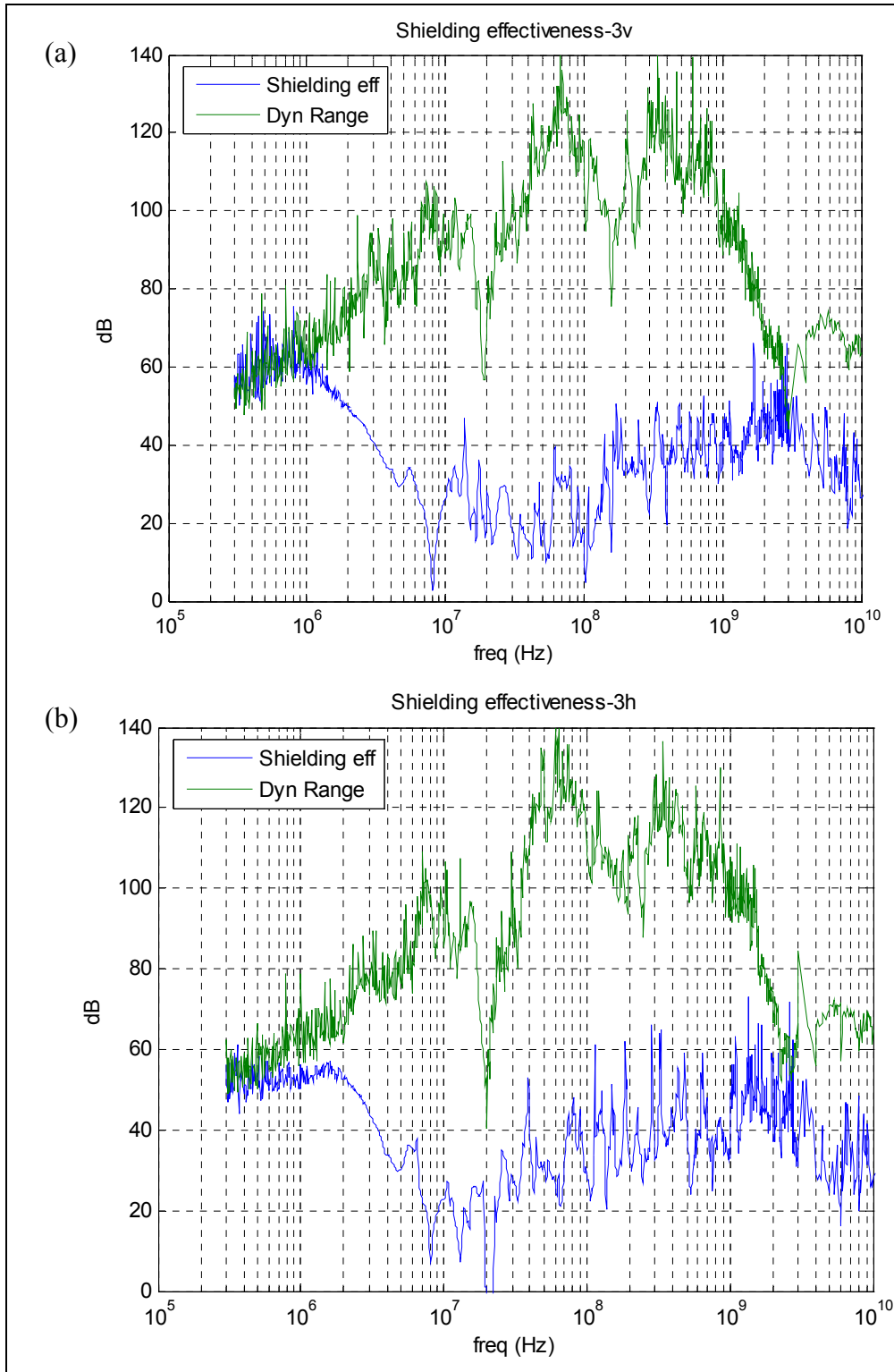


Figure 5. Shielding effectiveness for test point 3, (a) vertical polarization and (b) horizontal polarization.

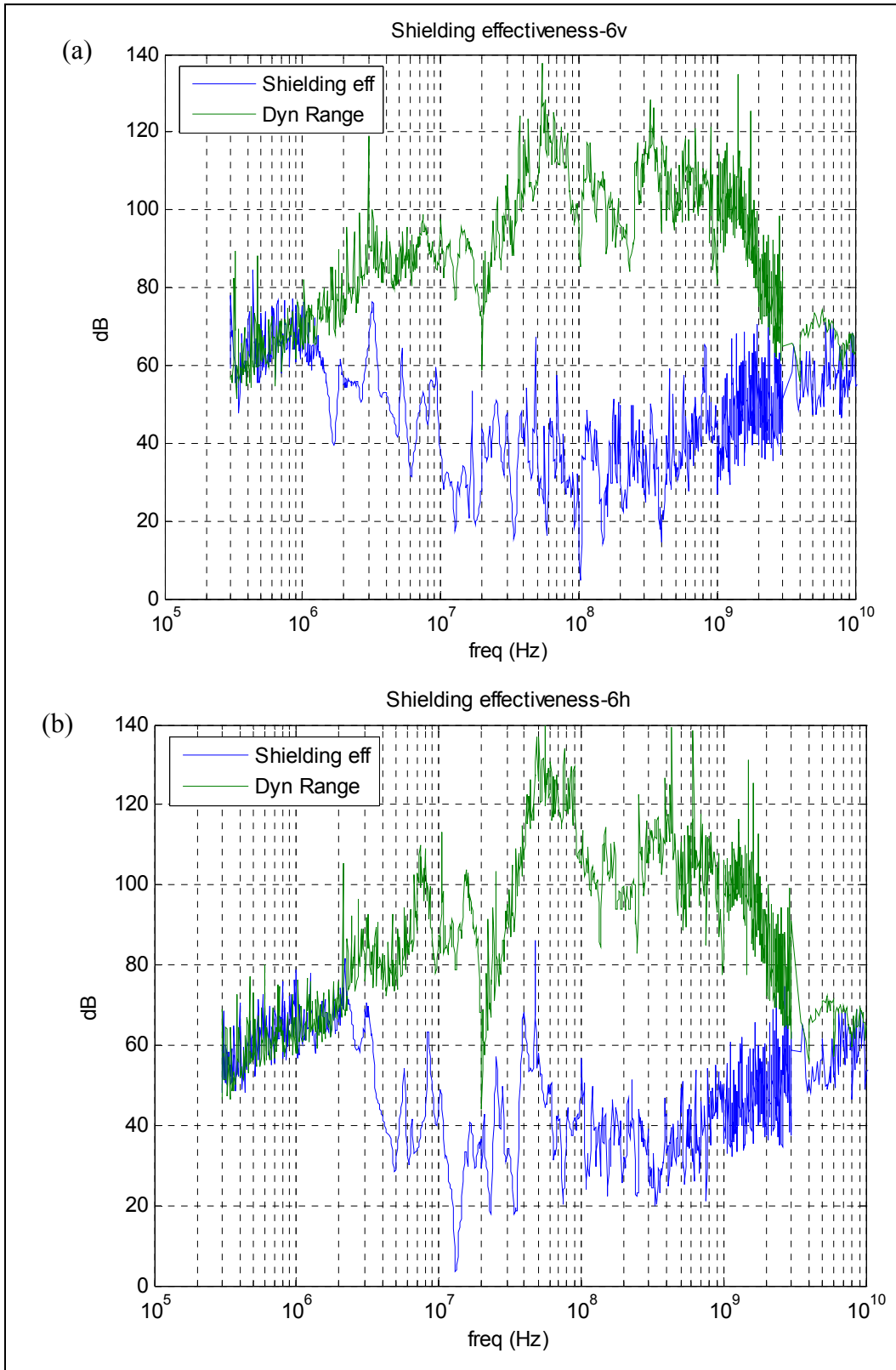


Figure 6. Shielding effectiveness for test point 6, (a) vertical polarization and (b) horizontal polarization.

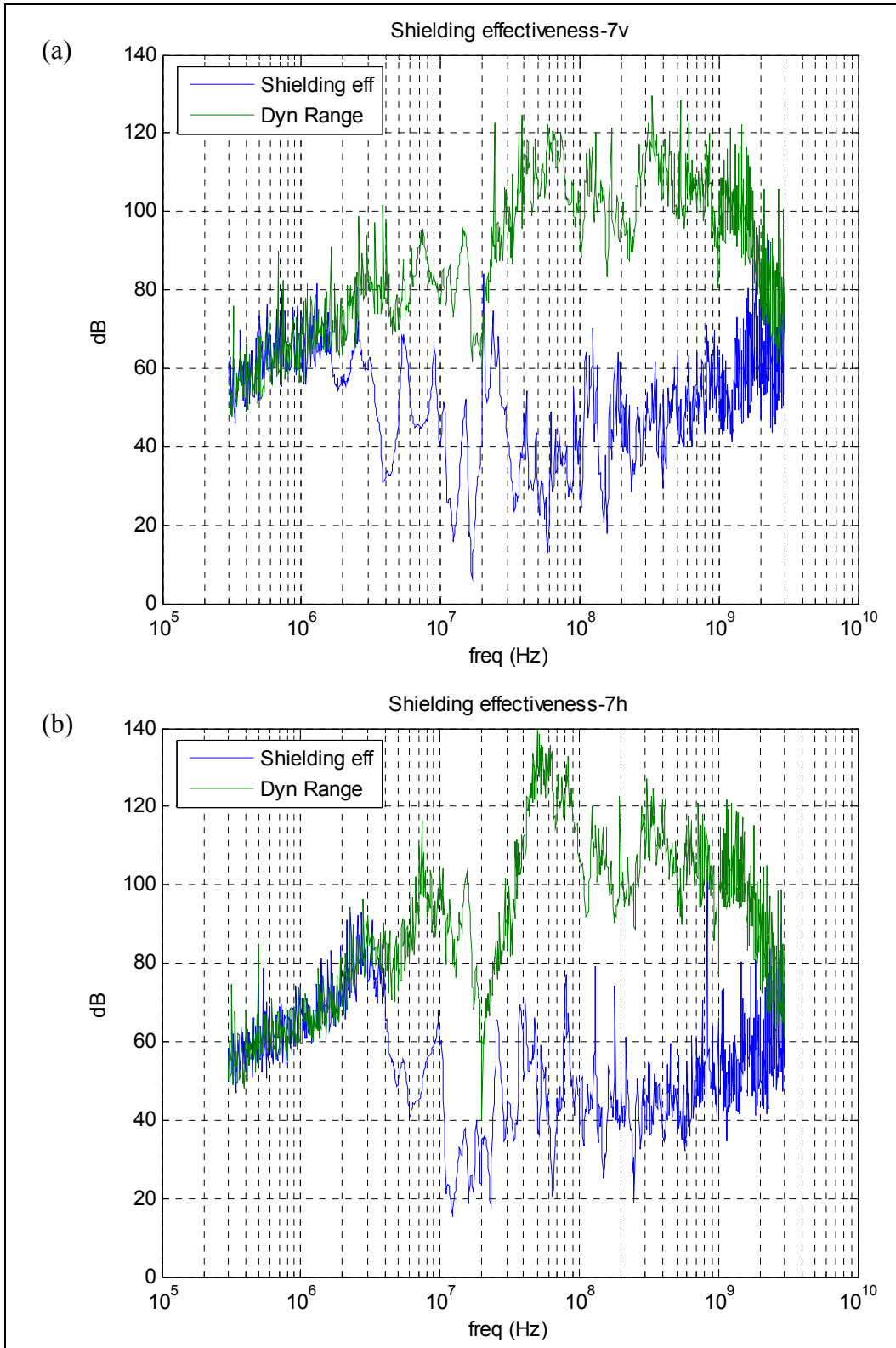


Figure 7. Shielding effectiveness for test point 7, (a) vertical polarization and (b) horizontal polarization.

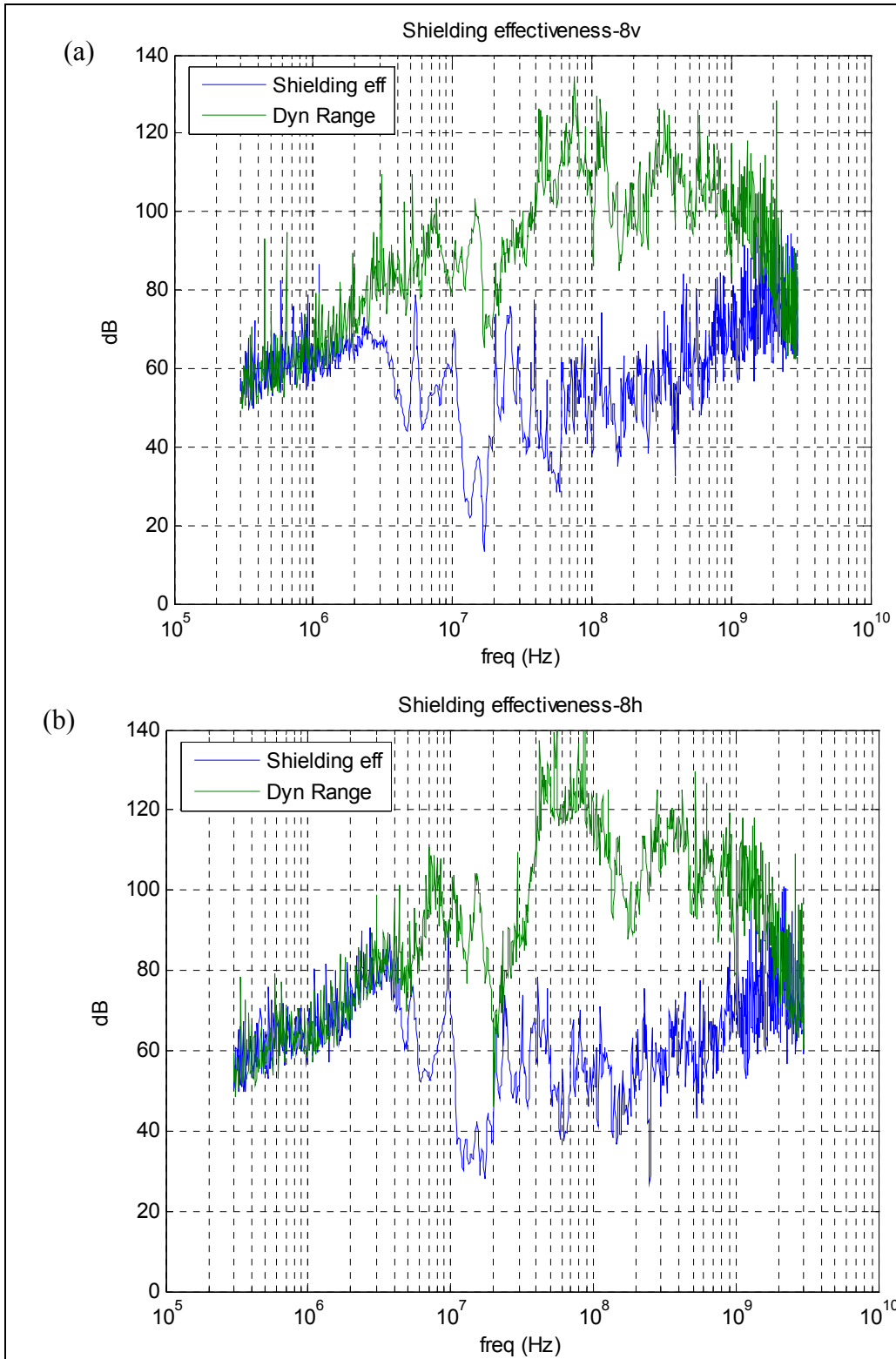


Figure 8. Shielding effectiveness for test point 8, (a) vertical polarization and (b) horizontal polarization.

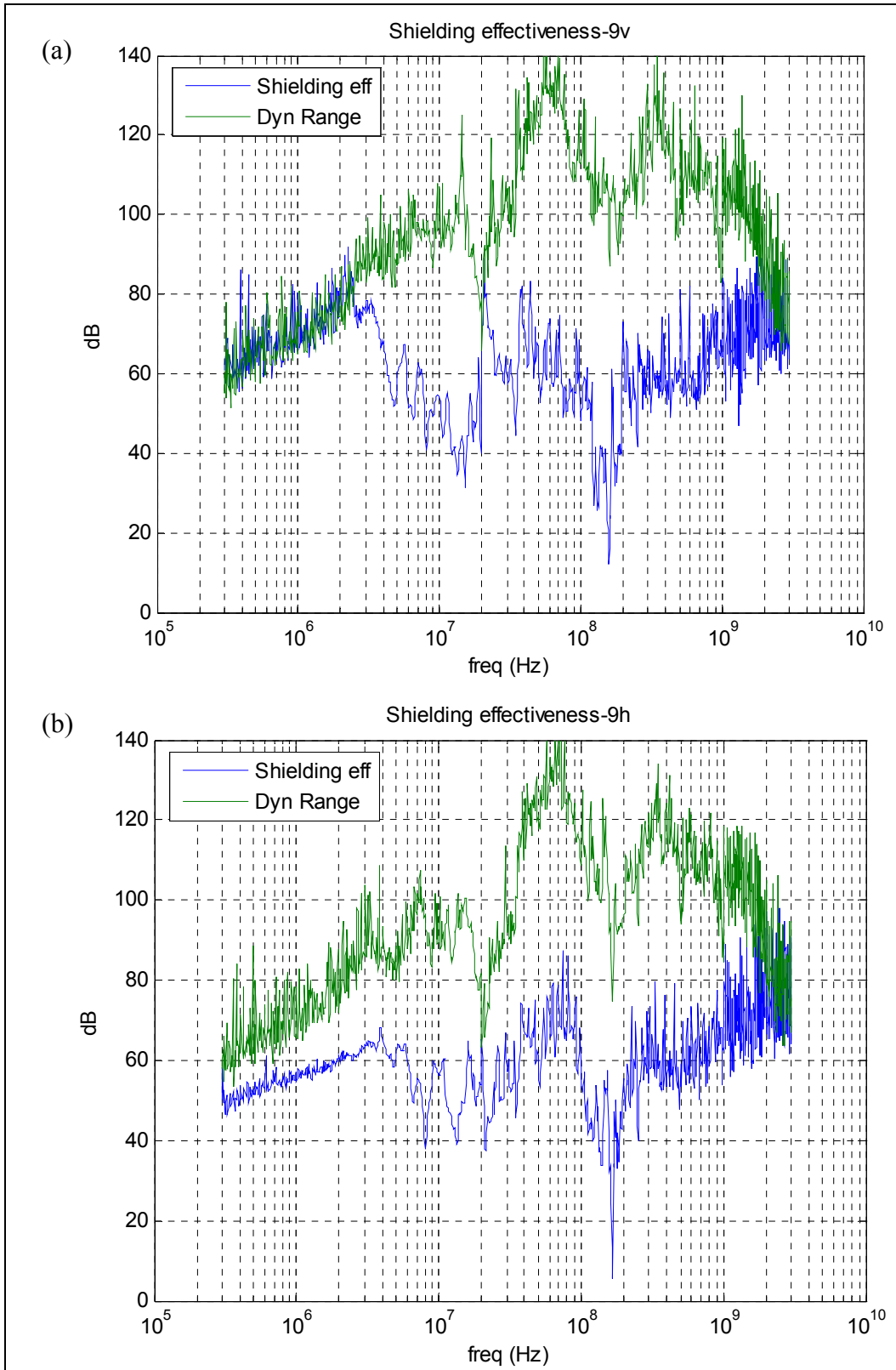


Figure 9. Shielding effectiveness for test point 9, (a) vertical polarization and (b) horizontal polarization.

Some specific measurements were performed at the request of Picatinny personnel. The patch-panel located between test points 6 and 7 had a small hole (~9/16 inch diameter) in it and had a hard signal wire running through it. This hole and wire created a source of leakage. At test point 6 we measured this leakage and then removed the wire and taped over the hole with copper tape, performing the measurements again. The copper taped reduced the signal leakage by at least 30 dB over the frequency band 2 GHz to 3 GHz, and greater than 10 dB over the range 3 GHz to 10 GHz. Limits in dynamic range of the TWT source/receiver channel prevented detecting more of an improvement between 3 to 10 GHz. The results of shielding effectiveness for both taped and untaped patch-panel in the vertical polarization is shown in figure 10.

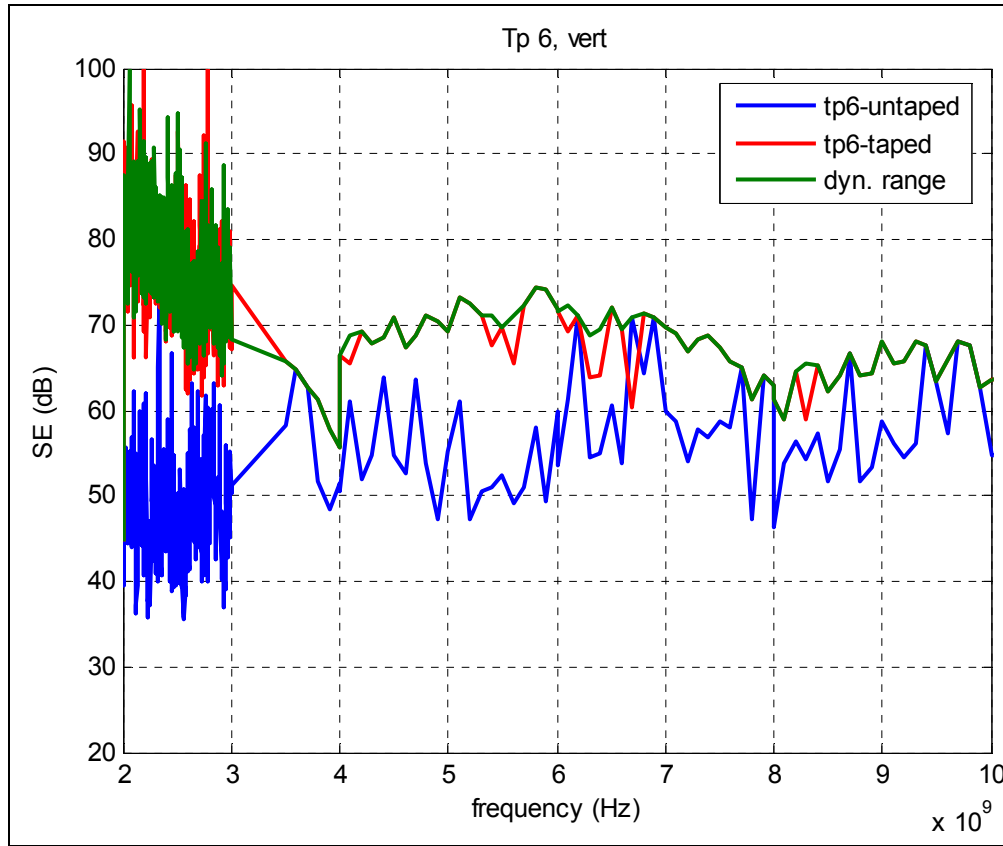


Figure 10. A 30 dB shielding effect occurs when taping over a 9/16 inch hole in a patch panel.

At frequencies determined by the physical size of the 28' × 12' × 8' room, the room acts as a resonating cavity. If we assume that a single and half wavelength are the most stable modes for the cavity oscillation, then the frequencies that might resonate during the measurement process are those closest to the resonant values. Table 2 shows the frequencies that would support cavity resonances for an empty box the size of the screen room. Of course, the screen room has work benches on at least 3 walls and RF absorber on 3 walls. The resonant frequencies calculated based on an empty room are idealized, and would not be expected to be precise. They serve only as a frequency range within which resonances would be expected to occur.

The idealized room resonances range from 17 MHz to 123 MHz. It is apparent from the shielding effectiveness curves shown for all test point (figures 3 through 9) that this frequency range contributes most to the leakage of the shielded room. Every test point measured shows some of its lowest shielding effectiveness in this range.

The HEMP MIL-STD calls for using fiber up to 1 GHz. However since it was desired to perform measurements up to 10 GHz and our fiber optic link was limited to 1 GHz, a hard-wire connection was used for frequencies between 1 and 3 GHz. In order to compare performance between the hard-wire and fiber optic connections and observe any differences in dynamic range or coupling, the measurements were performed twice in the 20 MHz to 1 GHz range for test points 1, 2, and 3. They were performed once with fiber optic linking the transmit and receive components, and another time with a hard-wire connection linking the transmit and receive components. In this frequency range there was found to be relatively good correlation between the results of each measurement set. The comparison for test point 2 for vertical polarization is shown in figure 13 and show results which differ by a few decibels at most.

5. Time Domain Analysis

The shielding effectiveness measurement described above provides a scalar value for all frequencies measured. These frequency domain (FD) measurements provide the amplitude to easily determine the shielding effectiveness, as defined in the MIL-STD. It would be of interest to predict the time-domain (TD) pulse shape of a multi-frequency impulse. In order to do this correctly, phase delay information is required. The phase was not recorded during this series of measurements. This could be performed in the future with a vector network analyzer such as the HP 8510C in the future. With this type of instrument, a measurement of phase delay for each frequency would also be recorded. With amplitude and phase available, a complete TD reconstruction could be performed and the waveshape of an impulse could be predicted.

The following analysis is less than perfect in that only amplitude data was measured. If we assume that the phase delay for all frequencies is zero, we can still calculate a predicted waveform outside the shielded room, from a sample input waveform. This prediction will be incomplete until such time as phase is measured. However, the calculation can provide insight into expected levels of leakage.

If an impulse is transmitted inside the shielded room, the TD signal received outside the room could be estimated by taking the Fourier transform of the transmitted impulse, multiplying it by the shielding effectiveness, and then taking the inverse transform to determine the resulting TD waveform. The resulting waveform would provide an estimate of the received waveform characteristics for insight and understanding. A phase of zero degrees was used when reconstructing these waveforms. However, shifting of phase could produce a varying TD signal.

It is unfortunate that the measurements required by the MIL-STD specify only amplitude and not phase. The measurements, which include phase information, can be performed in the future if necessary.

Two example waveforms were used for instructional purposes. First, a Gaussian waveform example radiated through the wall at test point 2 would produce the time domain output shown in figure 11. Second, an exponential impulse transmitted of the form $t \cdot \exp(-t)$ would produce an output as shown in figure 12.

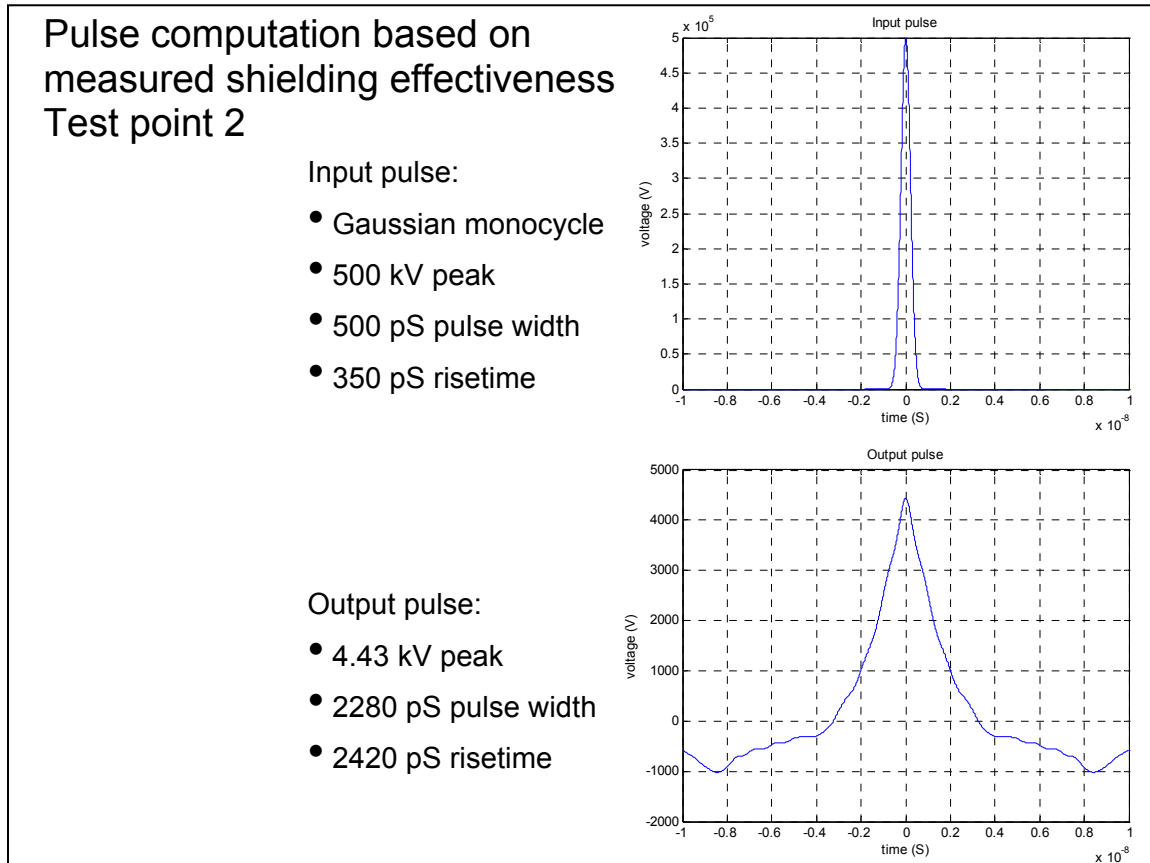


Figure 11. Example of TD reconstruction of impulse from a Gaussian impulse input.

Pulse computation based on measured shielding effectiveness Test point 2

Input pulse:

- $t \cdot \exp(-kt)$
- 500 kV peak
- 500 pS pulse width
- 117 pS risetime

Output pulse:

- 4.43 kV peak
- 2240 pS pulse width
- 1900 pS risetime

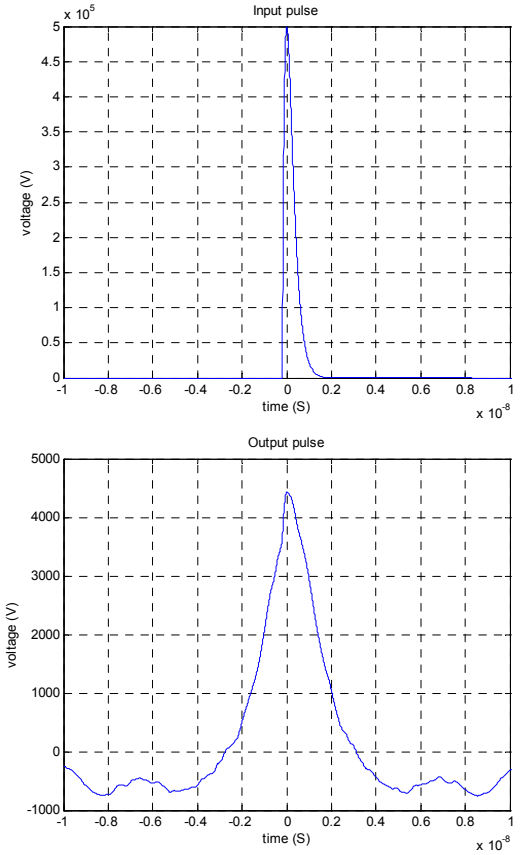


Figure 12. Example of effect on exponential impulse input.

If we assume a pulsed power source of 2.5 MV pulse into a 450 ohm load, we would calculate ~14 GW pulse into the load. If we assume a 25% efficiency of the PFN and horn, then the power transmitted is ~3.5 GW. The Fris equation for antenna power density radiated allows us to calculate the electric field at the wall of the shielded room (~1 m from the antenna).

$$P_D = \frac{P_t G}{4\pi r^2} = \frac{E^2}{Z_{fs}}$$

where

P_D = power density (W/m²)

P_t = power transmitted by source (W)

G = antenna gain

r = range from antenna (m)

Z_{fs} = impedance of free space

E = electric field (V/m)

This back-of-the-envelope calculation shows that 500 kV/m would appear at the inside wall of the shield room. The electric field appearing outside the screen room, based on the frequency-dependent shielding effectiveness measurements performed at test point 2, would suggest (see figure 11 and 12) that the electric field outside of the screen room would be ~4.5 kV/m.

This provides an example of the radiation levels that may exist. These levels are above those that would be permitted at the boundary of government property, but within safety guidelines for radar workers.

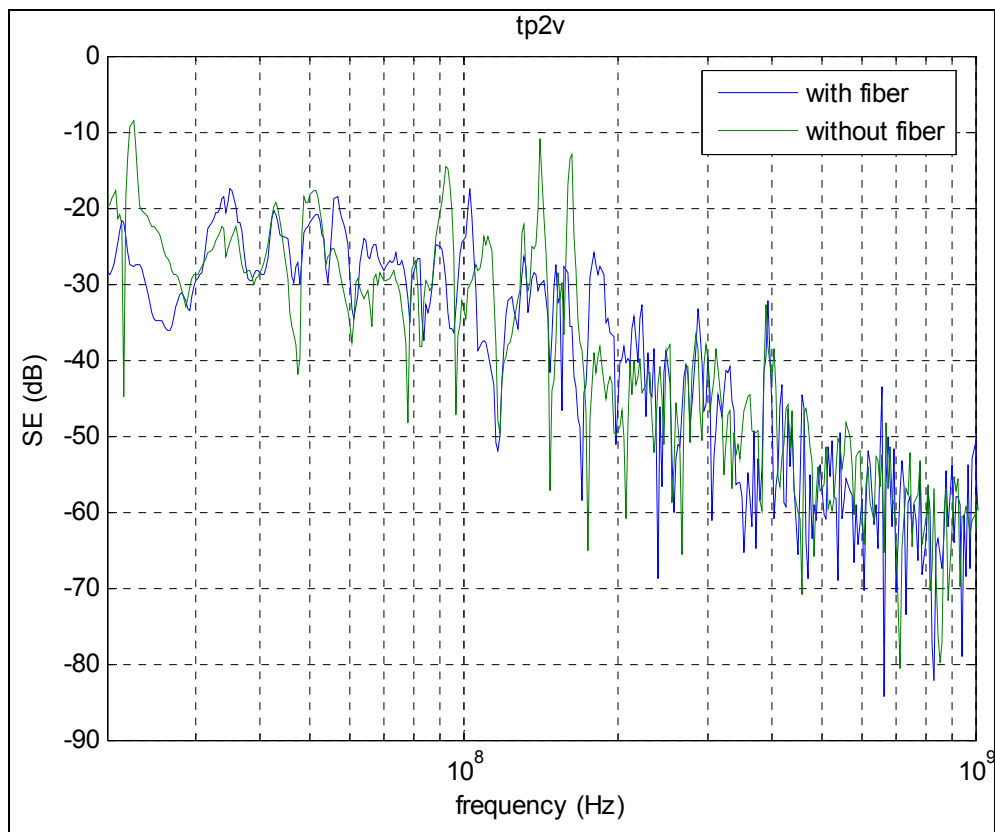


Figure 13. Comparison of data taken with and without fiber optic link for test point 2, vertical polarization. This shows good agreement.

6. Conclusions

The shielded room shows resonant leakage in the frequency range from 10 MHz to 123 MHz. This correlates well with the cavity resonances of the shield room. An 8 MHz signal stands out for test point 3. This is the location of the horn array patch panel.

The areas near both the front and back I/O panels (test points 3 and 6) had the worst shielding effectiveness. This was most likely due to the 9/16 inch hole in the I/O panel near test point 6, which was not sealed and also contained a hard-wire cable running through a hole in the horn array I/O panel at test point 3.

When operating any high-voltage transmitting equipment inside the shielded room, it is highly recommended that all open holes in the I/O panels be sealed tightly with metal plates, with

fasteners spaced every 1 inch, or as a temporary measure, with metal tape sealed firmly at all edges. These techniques are typical in HEMP hardening environments. Any hard wires running directly into the shielded room should be removed as well. It was shown that this significantly reduces RF leakage as would be expected.

The area around the door, test point 2, was also shown to have lower shielding effectiveness than test point 1. However, it is not clear from the data how much of this degradation was due to signal leakage through the I/O panel at test point 3.

The time domain analysis described in section 5 provides insight and predictions of electric fields expected outside of the rf shield room. It is shown that a 500 kV/m impulse radiation source would generate approximately 5 kV/m electric fields outside of the shield room.

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